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Employing Cantor sets for earthquake time series analysis in two zones of western Turkey

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Abstract In this study, a fractal approach is employed to analyze the seismic history of Fethiye and Simav zones in the West of Turkey. In this scope, a database, including the set of earthquakes in two seismogenic zones, is compiled. Applying fractal dimension and probability concepts, it is aimed to find out the occurrence probability of earthquakes having magnitudes equal to or greater than a threshold level. The results are analyzed in detail and relationships among the fractal dimension, threshold magnitude, probability intercept, and critical time scale are presented. The analyses revealed that activities in the Fethiye Zone are more frequent and continuous than those in the Simav Zone. As mentioned in previous studies, the critical time scales at certain magnitude thresholds can be referred to as the lower limit of the recurrence period of earthquakes in these zones.

1. Introduction

Engineering knowledge in the 21st century is able to analyze the characteristics of individual earthquakes to a reasonable degree. However, the spatial and temporal properties of regional seismicity are not yet well understood. Essentially, the fractal approach can be an alternative for recognition of the patterns belonging to this complex nonlinear dynamic system. The advantage of fractal analysis can be stated as the derived quantitative information that may be helpful in the dynamical mechanism of the seismic processes. Therefore, scale-invariant sets and fractal theory are proposed to analyze and evaluate complex natural phenomena. The scaling ability of power-laws is used to allocate the time-variable patterns in a fractal framework. In this context, Smalley et al. [1] applied fractal analysis to a dataset of earthquakes in the New Hebrides and stated that shocks between 1978 and 1984 demonstrate scale-invariant fractal clustering in time. The authors defined the fractal concept based on the idea that fractal clustering occurs with fractal dimension D, when fraction x of the intervals of length τ containing earthquakes is directly proportional to τ^{1-D} $(0 < D < 1)$. In their novel approach, considering four distinct regions, calculated fractal dimensions ranged between 0.126 and 0.255. This approach encouraged researchers worldwide to use the fractal dimension concept in time series analyses of earthquakes [2–5]. Fractal clustering of the temporal distribution of earthquakes was also proved by Kagan and Jackson [6]. Based on their long-term earthquake clustering analyses, they emphasized that the fractal dimension of the earthquake time series ranged between 0.8 and 0.9. Dattatrayam and Kamble [7] presented a good application of the temporal clustering of earthquakes using the fractal approach. Applying the method in two seismogenic zones in India (NW Himalaya and Delhi), D values were calculated as 0.254 and 0.193, respectively.

Raising the same issue, Kagan and Knopoff [8] proved that fractal behavior is observed in temporal and spatial properties of earthquakes. On a laboratory scale, Hirata et al. [9] proved that the behavior of the spatial distribution of acoustic emission centers was fractal, and the fractal dimension decreased with progressing cracks. The authors emphasized the possibility of estimating the occurrence probability of large earthquakes by the decrease in fractal dimension. Theoretical studies in the literature focused on the introduction of different models to different earthquake catalogues, in order to understand the nonlinear dynamic processes covering the temporal and

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spatial evolution of seismic patterns [10–13]. In the excellent review of Kagan [14], scale-invariant statistical distributions controlling seismicity, which, possibly, have universal values for exponents, was discussed. Different features are handled in scale-invariant oriented past studies. For example, Gutenberg and Richter [15] found that the magnitude of an earthquake was fit to a power-law distribution. Although recent studies revealed that the use of scaling laws seem comparatively feasible for modeling seismicity [16,17], several researchers in the literature advocate that the Poisson model is good for modeling the seismic activity of large events, due to its acceptable goodness-of-fit characteristics [18]. Surprisingly, scale-invariant methods were also used in the analysis of desert storm sequences [19], rainfall time series [20] and sea floods [21]. Moreover, recent specific studies based on the fractal dimension concept were conducted to simulate the dynamics of seismic activity. The study of Bhattacharya et al. [22] is very interesting. It endeavored to model the dynamics of lithospheric plates having fractal surfaces by temporal evaluation of the overlap lengths of two identical Cantor sets sliding over each other. Recent studies also include preliminary approaches for evaluation of the quantitative parameters of the self-similarity of the devastating Japanese earthquake in Tohoku [23]. Another study by Márquez-Rámirez et al. [24] investigated the fractal properties of two seismicity distributions prior to the 2003 Colima (Mexico) and 1992 Landers (USA) earthquakes. Emphasis was given to the idea that fractal dimension and afractality measures may be helpful in large earthquake premonitory studies. On the contrary, the scale-invariant character of the aftershock sequence of 1999 Chi–Chi (Taiwan) was investigated by Lee et al. [25]. Fractals were also utilized to evaluate the seismicity arising from volcanic activity [26]. The authors noted that the box-counting method was successful in scale-invariance detection, and the box fractal dimension was decreased as the threshold magnitude level increased. Besides, the study of Öncel et al. [27] investigated the spatial variation of seismicity by the fractal dimension of earthquake epicenters, which covered instrumentally recorded earthquakes of magnitude $M > 4.5$ that occurred in Turkey between 1900 and 1992.

In the light of this knowledge, the importance of the recurrence period is well acknowledged, since it is vital for the lifetime design of buildings in a region. Obtained critical time scales can be considered as the lower limit of the recurrence period for the two zones under consideration, which may be helpful in designing structures to withstand an event at a predetermined magnitude, carrying out risk analyses, etc. This study applies the fractal dimension concept, along with certain magnitude thresholds and probability methods, to perform earthquake clustering in the time domain for two active seismic zones in Western Turkey. It is considered that these results may be fruitful in design stages of the construction projects in two zones.

2. Box-counting method and Cantor sets

A fractal dimension is a ratio providing a statistical index of complexity, which is used to evaluate the variability of a pattern in its measured scale [28]. Self-similarity is a statistical property of fractal sets. Apart from area-perimeter and line divider methods, in some cases, use of the box fractal dimension method is essential. Herein, the box-counting dimension is simply defined as the parameter identifying the relationship between the size and number of boxes covering a set [29]:

$$N(r) = Cr^{-D}. \tag{1}$$

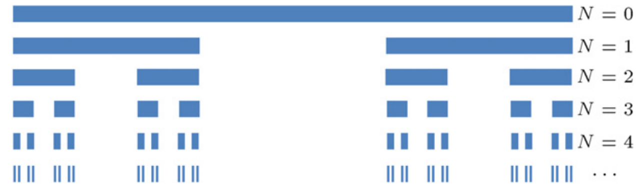


Figure 1: The deterministic triadic Cantor set. D value is constant for increasing N, which is equal to 0.6309.

In Eq. (1), $N(r)$ is the number of boxes covering the set with dimension r, C is a constant and D is the fractal dimension.

In many cases, the fractal dimension concept is evaluated along with the probability [30]. The Cantor set, introduced by G. Cantor [31], is a set of infinite points ranging between 0 and 1 (Figure 1). The Cantor set or Cantor dust is constructed by dividing a line of unit length into three segments: removing the middle third, two segments remain. In the next step, the remaining two lines from the previous step are individually divided into three segments and the two middle thirds are removed again. If this process is continued infinite times, finally, the total length of remaining line segments will approach zero. As the construction of the steps evolves, the middle third is removed from each of the segments, which ensure a fractal dimension calculated by log2/log3. Another type of Cantor set, which is not shown here, is the random Cantor set. In random Cantor set, the removed segment is randomly selected, however, this does not affect the fractal dimension value, which is equal to the one calculated by construction of the deterministic Cantor set. The random Cantor set is a beneficial tool for evaluation of the point events irregularly clustered in the time domain [32].

As mentioned earlier, in order to fulfill the aims of this paper, the fractal dimension is reconsidered by the probability concepts. In this scope, the probability of including a line segment at a step ratio scale, r, is defined as:

$$P(r) = N \times r. \tag{2}$$

Taking the natural logarithm of the two sides of Eq. (1), it is easy to say that D is equal to $\ln(N)/\ln(r^{-1})$. Thus, at step zero ($N = 0$), there is only one line in hand, and the probability of inclusion of a line segment by a set of ratio scale ($r = 1$) is $P(r) = 1$. Proceeding in Figure 1, at step 1, when $N = 2$, $r = 1/3$. In this way, at steps 2 and 3, N values are 4 and 8, whereby, corresponding $P(r)$ values are calculated as 4/9 and 8/27, respectively. It is obvious that the fractal dimension is an indicator of the relationship between $P(r)$ and r. Therefore, the following equation can be written:

$$P(r) = r^{1-D}. \tag{3}$$

The next step is to establish an equation concerning the magnitude and time parameters, taking into account the logic in Eq. (3). Therefore, assuming T_k as a magnitude threshold, the number of events greater than or equal to certain magnitude Y_j can be determined easily ($Y_j = 1, 2, 3, \dots, R$). It should be noted that R is the total time interval comprising the earthquakes occurring in a certain period.

For a better understanding of the application of theory, similar to the yardstick concept in the line divider method, time scales ε_j (for $j = 1$ to s) are used to segment the total period into equal time intervals, having a value of (R/ε_j). By use of this knowledge, the cumulative frequency of time intervals,

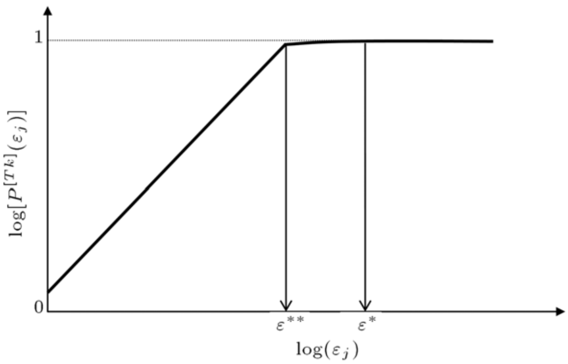


Figure 2: A sample probability-time scale plot.

including at least one event having a magnitude greater or equal than a threshold, can be easily calculated:

$$p^{[T_k]}\left(\varepsilon_j\right) = \frac{N^{[T_k]}\left(\varepsilon_j\right)}{R\varepsilon_j^{-1}}. \tag{4}$$

Taking Eq. (3) as a guide, the following relationship can be established:

$$p^{[T_k]}\left(\varepsilon_j\right) = \varepsilon_j^{1-D}. \tag{5}$$

Equalizing the right sides of Eqs. (4) and (5), while taking the natural logarithm of the two sides of the resulting equation, the following expression is obtained:

$$\ln\left[\frac{N^{[T_k]}\left(\varepsilon_j\right)}{R\varepsilon_j^{-1}}\right] = [1-D]\times\ln\left(\varepsilon_j\right). \tag{6}$$

Plotting $\left[\frac{N^{[T_k]}(\varepsilon_j)}{R\varepsilon_j^{-1}}\right]$ against ε_j on a log–log paper, a regression line can be drawn for the linear part of the curve. It is apparent that the slope of the linear part of this curve should be equal to $(1-D)$. As scrutinized by Chen et al. [32], Figure 2 demonstrates the tendency of the $P-\varepsilon_j$ variation on a log–log scale; starting with a linear trend for a minimum value of P, and reaching to a probability of 1 at a critical time scale (ε^*). This value is a definition of the recurrence period, and is considered the minimum period computed for earthquake events greater than or equal to a threshold value. As can be observed from outcomes of this study, when the probability approaches 1, the $P-\varepsilon_j$ variation becomes curvilinear and the part of the curve between time scales 0 and ε^*, which include random events, is considered to be scale-invariant [1,32]. In order to define a time series having a regular fractal structure, another definition of the critical scale is proposed [32]. The regression line of points of probability 1 is extrapolated and the critical scale is redefined as ε^{**}. In this study, ε^{**} is accepted as the critical scale, since the approach of Chen et al. [32] seems very plausible. A computer code is prepared for enhancing the calculations. It should be emphasized that the time scale is calculated by 3^u, where the exponent u ranged between 0 and 20.

3. Time series analysis by Cantor sets in two zones of western Turkey

Extending from Italy to Burma, Turkey is within the Alpine–Himalayan orogenic system [33]. Tectonic elements are the source of the majority of earthquakes in Turkey as well as surrounding areas. The Anatolian Plate underlies the Anatolia and Aegean Sea. The Anatolian Plate moves to the southwest of Turkey by the subduction along the Hellenic Trench. East–west oriented grabens are responsible for the seismicity in the Aegean region [33]. The Aegean region and Turkey have experienced countless damaging earthquakes in the past, and these seismic actions have been responsible for enormous loss of life and property. The seismic activity data includes earthquakes occurring between 1900 and 2012 within the boundaries of the two regions, which is compiled from the database of the Turkish Republic Disaster and Emergency Management Presidency, Earthquake Department [34]. The earthquake data is transferred in a single database by converting all other types of magnitude to local magnitude (M_L). The equations proposed by Yılmaztürk and Bayrak [35] and Kalafat [36] were preferred in preparation of the database.

Two zones under consideration are the Fethiye and Simav zones in Western Turkey, of which the boundaries are described in the study of Erdik et al. [33]. The authors made zonation using the seismicity database compiled from various resources and tectonic mechanisms of the regions. The Simav fault zone is known to traverse from Sındırgı to Sincanlı County borders. Having a right-lateral strike slip motion, this fault system has five sub-fault segments, including Sındırgı, Simav, Şaraphane, Banaz and Sincanlı [37]. The Gutenberg–Richter relationship belonging to the fault zone is $\log(n) = -0.846 \times M_L + 5.858$ with a R^2 value of 0.99. On the other hand, The Fethiye zone is located to the east of the Mediterranean Sea, and it is assessed that this area is within the southwest moving Hellenic Trench in the west and Pliny and Strabo trenches in the east. Evidences delineate two different scenarios documenting that the Fethiye–Burdur fault zone and the faults forming the Pliny Trench are thought to be responsible for the high tectonic activity in the region [38]. The Gutenberg–Richter relationship for the earthquakes occurring inside the boundaries of this zone is calculated as $\log(n) = -0.718 \times M_L + 5.644$ with a R^2 value of 0.97.

Taking the study of Erdik et al. [33] as a guide, the boundaries of the two regions are defined, and the database is constituted in two zones. The earthquakes from 1900 to 2012 are considered in constitution of the database. The location of the two zones in Turkey, as well as the seismic activity in those two zones, is illustrated in Figure 3. Additionally, histograms of the magnitudes of earthquakes in the two regions are depicted in Figure 4. As can be seen from Figure 4, the number of seismic activities in the Fethiye zone (681) is at a higher level, in comparison with that in the Simav zone (374). However, it should be questioned whether this point of view is valid or not by fractal analysis.

The results of fractal analyses in two zones are given in Figure 5, and Table 1 tabulates the data in these figures. The first result that is apparent from the test results is that the fractal dimension (D) decreases as the magnitude threshold increases, which stresses that earthquake sequences show a multifractal behavior in terms of magnitude. Comparing the D values in two zones, for the M_t values of 4 and 5, the Fethiye zone seems more active in comparison with the Simav zone. After an M_t value of 6, D values almost equalize in the two zones, which implies that seismic activities are not clustered in the two zones after this threshold value. On the other hand, the critical scale increases with increasing M_t, which is an expected outcome. Similar to D, P value decreases as the magnitude threshold increases. This is also an expected result. The probability of activity occurrence should decrease in greater magnitudes because of the decreasing frequency of the events. One thing that should

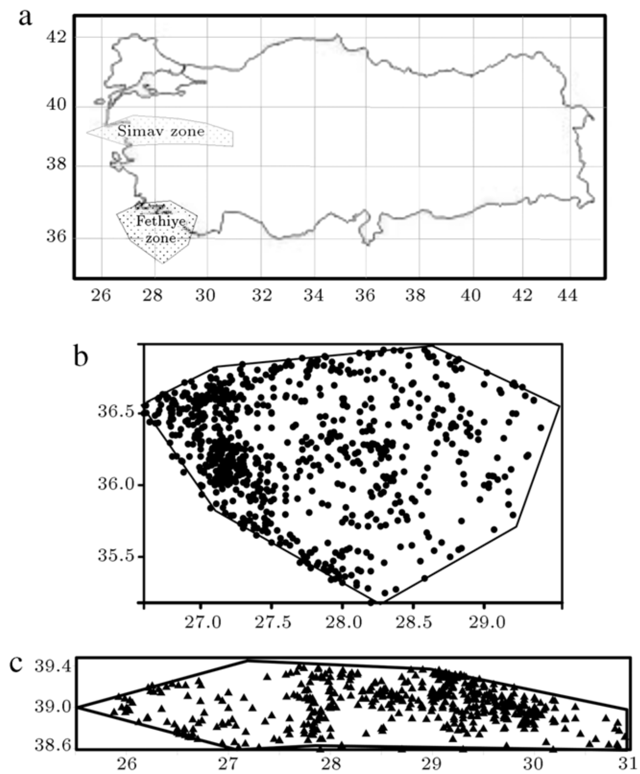


Figure 3: Earthquakes of $M > 4$ within the boundaries of two zones under consideration since 01.01.1900 (a) Location of two zones in Turkey (b) Fethiye Zone (c) Simav Zone.

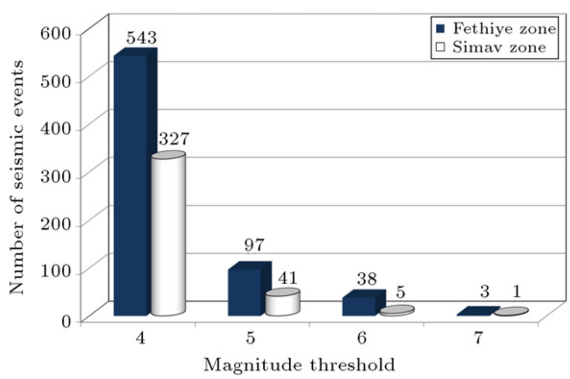


Figure 4: Distribution of the magnitudes of earthquakes in two regions.

Table 1: Outcomes of the fractal approach: Fractal dimension, critical time scale and intercept probability values in two zones are tabulated.

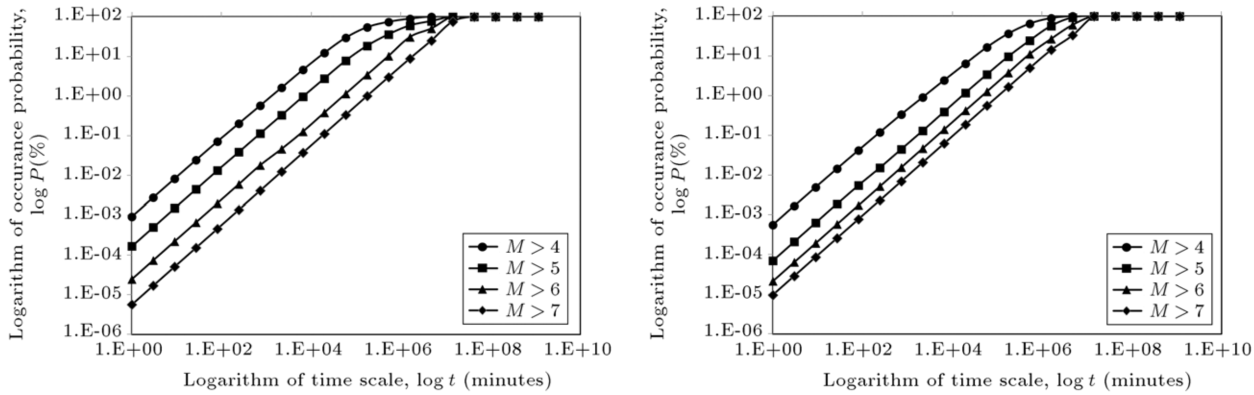
M_t	Fethiye zone			Simav zone		
	Total events = 681			Total events = 374		
	D	ε^{**} (min)	P	D	ε^{**} (min)	P
4	0.0621	106 734	9.234×10^{-4}	0.0523	440 190	5.537×10^{-4}
5	0.0440	631 105	1.685×10^{-4}	0.0351	1 365 379	6.992×10^{-5}
6	0.0187	2 686 690	2.453×10^{-5}	0.0186	6 014 880	2.137×10^{-5}
7	0.0021	19 051 184	5.687×10^{-6}	0.0014	53 338 169	9.564×10^{-6}

be underlined is the difference between ε^{**} values. For M_t values greater than 4, 5, 6 and 7, ε^{**} values are calculated as 74 days, 1.2 years, 5.1 years, and 36.2 years in the Fethiye zone. Nevertheless, ε^{**} values for the same magnitude thresholds are calculated as 305 days, 2.59 years, 11.44 years and 101.5 years in the Simav zone.

The variations of fractal dimension values with threshold magnitudes are given in Figure 6, which seem to have extremely meaningful relationship in terms of R^2 values. Additionally, the critical time scale exponentially increases with the magnitude threshold, as given in Figure 7. The almost parallel lines in Figure 7 reveal that the critical time scales in the Fethiye zone are smaller in comparison with those of the Simav zone, which also indicate that seismic events are more frequent and sequential in the Fethiye zone. Since the critical time scale is a descriptor of the unchanged fractal structure, this parameter may be a descriptor of the lower limit of the recurrence period of seismic events [32], and the behavior in this figure seems to be logical. Comparing the two zones, the critical time scales in the Fethiye zone are smaller, which may be an indicator of smaller recurrence periods. The fractal dimension-intercept probability results in semi-logarithmic scale are given in Figure 8. It should be noted that a single regression curve is the descriptor of the data set as a whole. Lastly, Figure 9 shows the relationship established between the critical time scale and the intercept probability. Similar to Figure 8, a single exponential curve is the descriptor of the relationships in two datasets. The behavior of the two curves is explained by Smalley [1]. It was emphasized that, as the clusters are more isolated, decreases are recorded in computed fractal dimension values. Smaller P values cause longer recurrence periods due to the formation of sparser clusters. Conclusively speaking, sparser earthquakes occur at higher magnitude thresholds, which cause an increase in critical time scales, as observed in the results of this study.

Unifying the regression results in Figure 9 and taking Eq. (6) into consideration, the following equation can be obtained for earthquakes in the two regions:

$$\varepsilon^{**} = \frac{88.099}{\varepsilon_j^{1.044\cdot(1-D)}}. \quad (7)$$



(a) Fethiye zone.

(b) Simav zone.

Figure 5: Variation of the probability with time scale: (a) Fethiye zone, (b) Simav zone.

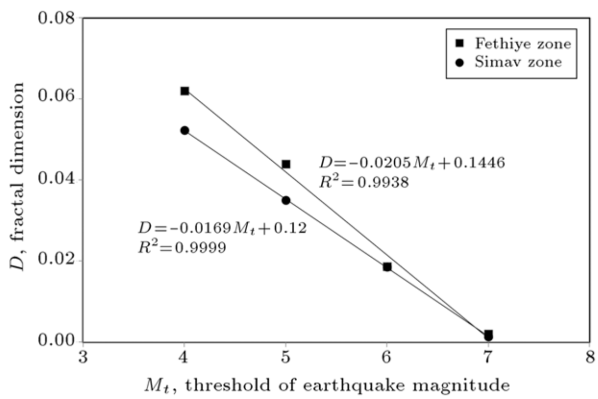


Figure 6: Linear dependence of fractal dimension on predetermined earthquake magnitude in two zones.

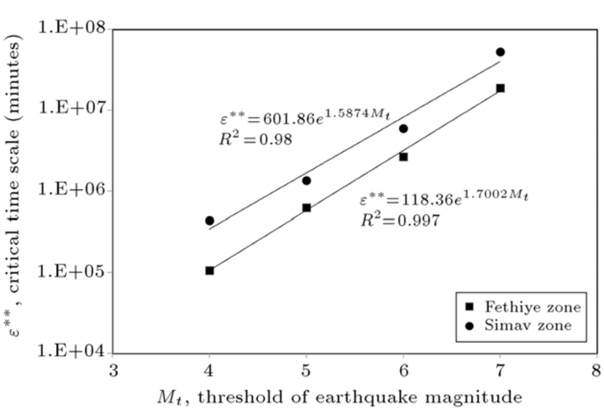


Figure 7: Variation of critical time scale with earthquake magnitude threshold.

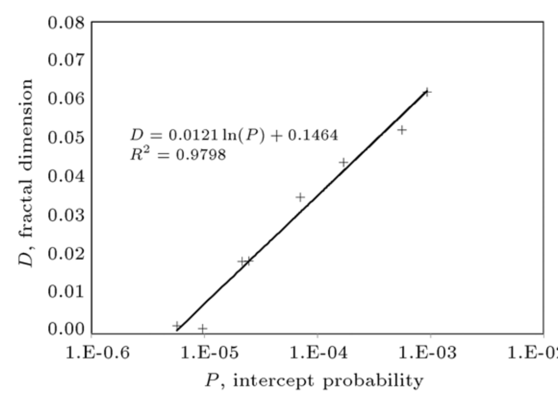


Figure 8: Semi-logarithmic plot of fractal dimension against intercept probability. Data belonging to the two zones can be represented by a single trendline.

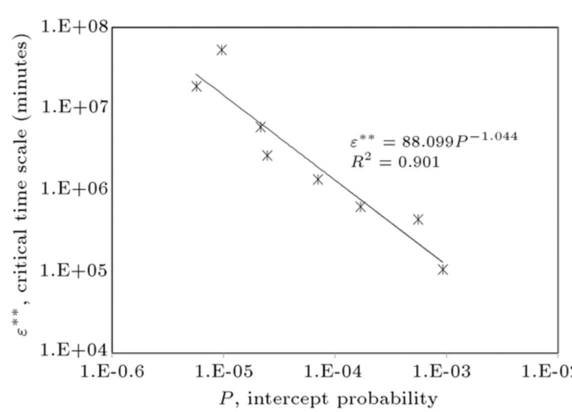


Figure 9: Log–log plot of critical time scale against intercept probability. Similar to the *D*–*P* relationship, a single exponential expression identifies the data belonging to the two zones.

Basically, seismic events in a region have five identifiers, namely, occurrence time, three dimensional coordinates, and magnitude. Fractal clustering can be applied to model any of these subsets. As mentioned in the introduction section, spatial and temporal clustering of earthquakes has attracted the attention of many researchers worldwide. Because it is well acknowledged that the seismic events in a region are not fully random, the fractal approach can be used to perform a preliminary approach for evaluation of the seismicity in a region. In comparison with the Poisson model, which can successfully model purely random processes, fractal models can be preferred in the modeling of processes exhibiting scale-invariant behavior [1]. Application of the Poisson model also necessitates sorting out foreshocks and aftershocks, owing to the independence rule of the Poisson model. Therefore, valuable quantitative information obtained by fractal analyses is helpful in understanding the dynamical mechanisms of seismic activities. Constructing networks providing high-quality data with sensible data acquisition devices, the fractal dimension parameter, computed using the data, including temporal and spatial distributions and number of occurrences, may be fruitful in estimation of the recurrence period of seismic events. A detailed seismic threat analysis is essential, especially for engineering structures of higher importance, including high-rise buildings, nuclear power plants, hospitals, bridges and dams. Extensive life and property loss will be prevented by a wisely engineered structure falling in the above depicted categories. On the other hand, individual seismic threat analysis for these structures is not a practical approach. Instead, regional seismic threats, and micro and macro zonation maps can be prepared. Preparation of microzonation maps necessitates a correct assessment of the seismic hazard in the region under investigation. Therefore, fractal analysis for lower bound estimates of the recurrence period, along with the fault maps, may be a valuable tool for seismic hazard predictive analysis.

Future research in this area can be focused on the temporal clustering of earthquakes in the remaining zones of Turkey and other parts of the world. Along with temporal clustering, spatial clustering of earthquakes can give reasonable outcomes for understanding the nature of earthquakes in miscellaneous regions.

4. Conclusions

In this study, Cantor set fractal distribution and probability concept in the time domain are used to evaluate recurrence periods, based on certain earthquake magnitude thresholds. Two zones, namely, Fethiye and Simav zones, are selected, due to their satisfactory data quality and quantity. Fractal analyses in two zones indicated that, for the same magnitude threshold (M_t) value, fractal dimension values (D) calculated for the Fethiye zone are greater than those of the Simav zone, which indicate a more active seismic zone. D values in the Fethiye zone are calculated as 0.0621, 0.0440, 0.0187 and 0.0021 for M_t values of 4, 5, 6 and 7, respectively. On the other hand, for the same M_t values, D values in the Simav zone are calculated as 0.0523, 0.0351, 0.0186 and 0.0014, respectively. The number of earthquakes in the Fethiye and Simav zones recorded between 1900 and 2012 are 681 and 374, respectively. Both fractal analysis results and number of seismic events reveal that activities in the Fethiye zone are more frequent and sequential. Besides, after an M_t value of 6, D values almost equalize in two zones, which imply that, after this threshold value, seismic activities are not clustered in two zones. When the M_t value surpasses 7, D values approach to 0, and seismic activities have extremely small probabilities in greater M_t values. Taking ε^{**} values for the lower limit of the recurrence periods, a comparative approach reveals that the ratio of ε^{**} values of the Simav zone over those of the Fethiye zone range between 2.23 and 4.12. For M_t values greater than 4, 5, 6 and 7, ε^{**} values are calculated as 74 days, 1.2 years, 5.1 years, and 36.2 years in the Fethiye zone. On the other hand, ε^{**} values for the same magnitudes are computed as 305 days, 2.59 years, 11.44 years and 101.5 years in the Simav zone. ε^{**} values can be a plausible parameter for seismicity assessment, and needs further discussion. Considering temporal behavior, the number of events and fractal dimension values, the results of this study show that seismic sources in the Fethiye zone are more active in comparison with the Simav zone. In this way, it can be stressed that Eq. (7) and other derived relationships among fractal dimensions, including critical time scale, intercept probability and the magnitude threshold of high R^2 values, can be used to evaluate the properties of activities in two seismogenic regions.

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